Space Propulsion Systems Health Management

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Large Rocket Engine Environments

- Hot
- Cold
- Vibration
- Volatile fluids
- High pressures
- Extreme fluid velocities (flow rates)
- Fast control loops and failure propagation
- Industry seldom operates in these regimes

- One failed ground test ~$200M impact

Engine Key Issues

- Very limited ground tests with limited states of operation (critical for prognostics)
- Small sample set analysis
- Need adaptive level of autonomy

- New nuclear propulsion systems
  - Military reactors
  - Harsh environments
  - Little or no maintenance

Dichotomy Mass vs. Complexity

- Increased mass (ruggedness) vs. complexity
- Anvil needs no HM…
  - Russian engines
  - Apollo vs. Shuttle complexity
  - Space Ship 1 vs. Apollo
  - (Some desire thousands of sensors)
- Lighter engines RS-??, RL-?? Etc.
  - SSME extreme power intensity with materials and components operating at their physical limits
  - Needs more HM
  - Updated SSME are heavier to address operational issues and increased margins (quantify 13%?)

Legacy Systems

- Limited, incomplete sensor coverage
- Many fault ambiguities
- Difficult or impossible to add needed instruments because equipment modifications require recertification
- Result--very limited HM without serious modification

- Lesson--HM must be built in as a system philosophy to achieve long-term operational cost objectives

Key Engine HM Issues

- Issues driving engine health management size, scope, function, coverage, cost, etc.
  - Ground HM vs. real-time on-board HM
  - Manned vs. unmanned (variable autonomy)
  - Solid vs. Liquid vs. Mixed engine systems
  - Others…

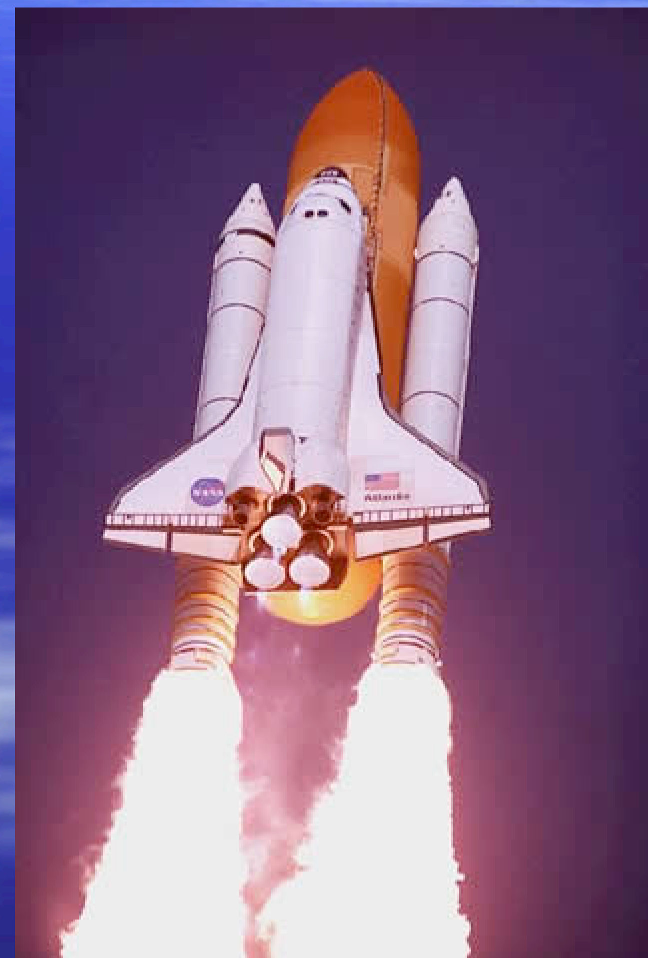
Working Space Propulsion Examples

- Space Transportation System (STS)
- DC-XA
- X-33 (never completed the build)
- X-34 (build, never flew)
- X-38 (no engines, little HM)
- Boeing Delta IV
- Lockheed Atlas V

- Electronic engine controllers
  - SSME, RS-68, RL-10, RD-180
  - All engine mounted, custom designs with little or no commonality
  - Engine mounted vs. vehicle mounting is a design maintenance and political choice

Space Transportation System (STS, Shuttle) Characteristics

- Mixed propulsion system (solids and liquids)
- Engines are line replaceable units that are replaced
- Space Shuttle Main Engine (less than 100 sensors each)
- ???number of shuttle sensors???
- Human rated (only system that is)



X-33 Characteristics

- All liquid system (linear aero spike engines)
- Autonomous vehicle control (people were payload)
- Remote health nodes—small, powerful, reconfigurable, rugged, distributed
- Automated diagnostics
- System had on order of ~2000 sensors

DC-XA Characteristics

- All liquid system
- Sub-orbital vehicle
- Automated check-out system
- Distributed data system
  - Plume diagnostics system
  - Hydrogen leak detection system
  - Vibration analysis system
  - Etc.
- Launch operations crew of 3, total service crew of 17, totally transportable
- DC-XA vehicle flew successfully 4 times prior to a landing crash resulting in destruction (DC-X flew approximately 10 times)

Delta IV, Atlas V Characteristics

- New expendable, liquid engine systems
- Conventional monitoring systems (extensive HM not seen as needed for expendables)
- Fixed, dedicated launch facilities

Commercial and Industrial Compared to Space Systems

- Commercial aviation system management examples
  - Refer to prior chapters…
  - Issues
    - Not radiation tolerant or hardened
    - Not built for space temperature regime
    - Hundreds of vehicle systems vs. fleet sizes of 3 or 4
- Industrial system management examples
  - Petroleum and chemical industry--super critical, hazardous systems
    - Issues
    - Unlimited space and weight to implement hardware
    - Intentionally create benign environments
    - Very large statistical sets
    - Relatively easy access to components
    - Failure can result in large loss of life
    - System shut down and restart takes massive time and financial resources
  - Heavy machinery (earth moving, mining, farming, railroads)

Existing Rocket Engine Systems

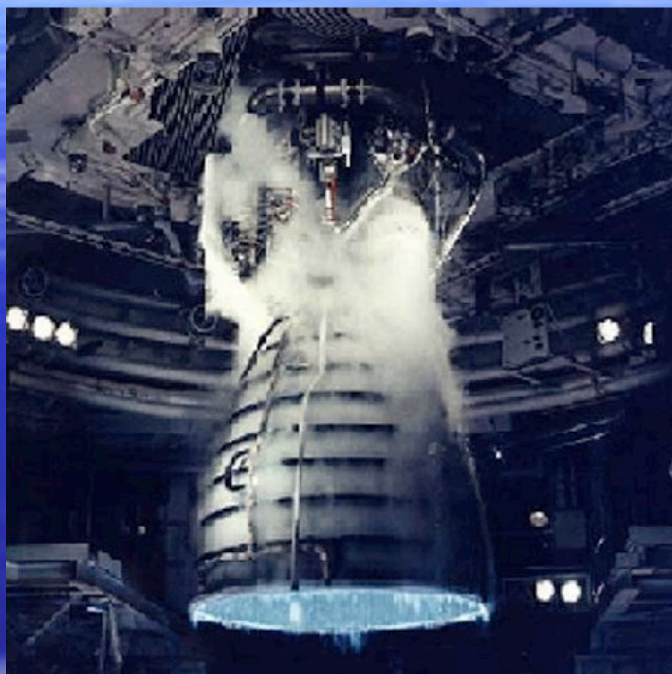
- Typically centralized systems
- Little use of smart (intelligent) sensors
- Redline monitoring for safety warnings
- Diagnostic software exists--custom, engine specific
- Failure can be costly
- Human life can be lost

Engine Sensors and Actuators

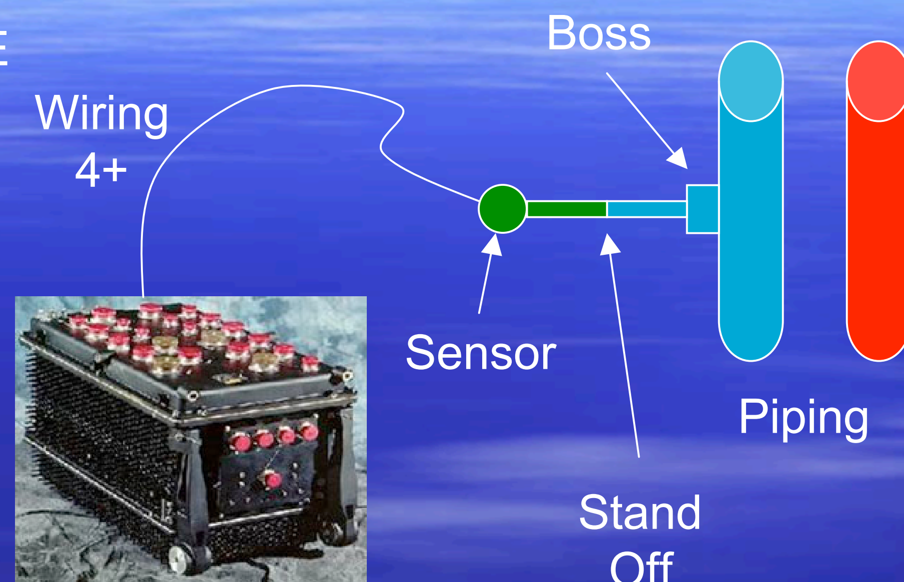
- Monitoring of engine system is primarily through pressure and temperature measurements
- Recent developments include vibration monitoring and analysis (New pump fed systems will have vibration monitoring with engine shut-down authority)
- Flow measurement issues
  - LOX compatibility--system safety
  - Intrusion into flow system
  - Weight impacts
- Direct mounted instruments are difficult to achieve due to the harsh engine environments

- Practical example…

Practical Engine Sensor Example



SSME



SSME Controller

Pressure sensor size, weight, mounting, stand-off tube, wiring, redundancy, processing → weight and reliability impacts

Sensor Development Needs

- Improved reliability--sensor reliability tends to be low…engine control people want to seriously limit the number of sensors
- New capabilities and functions
- Need plug-n-play capabilities
- Extensive built-in tests and verification capabilities
- Sensors for Propulsion Measurement Applications (http://www.spie.org/Conferences/Calls/06/dss)

What is needed for new engine management and control?

- More computing power
- Radiation hardening
- Environmental hardening and envelope extension both hot and cold
- Improved redundancy management
- Intelligent instrumentation implementation
- Faster software verification
- Improved system modeling
- Modular hardware and software designs

Communication Interface Issues

- Engine controller is a closed loop system where sensed information results in control command modifications
- Need intelligent, redundant data and command busses based on solid, proven, rugged standards
- System must be open architecture (open to all vendors without license and royalty fees)
- Critical and non-critical data delivered in high, medium, and low bandwidth possibly sharing the same busses
- Significant design and integration issues across the vehicle system

Propulsion System Model Issues

- Requires extensive simulation, modeling, analysis, and hardware tests to
  - Function safely and effectively
  - Perform failure detection, isolation, and recovery
  - Optimize fault coverage
  - Minimize number of sensors
- Requires highly integrated, multiple domain models for complex, time and safety critical systems
- Accurate models take years and numerous engine operational tests to refine and validate performance (diagnostics then prognostics)
- Processing limitations greatly limit the number and complexity of models running in real time
  - Your desktop processor will not fly in space for critical functions
  - There are few radiation hardened processors
  - Simplified models reduce monitoring and control capabilities

Conclusion

These issues, along with design specific technical and human factor issues, must be evaluated, understood and incorporated into early system requirements, then acted upon during all design phases to fully implement engine health management systems

Engines do not fly without a vehicle…